Justification of W-band FMCW radar functional blocks parameters using high-level system model

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Abstract. The paper presents a high-level system model of a W-band frequency-modulated continuous-wave radar which allows to determine and optimize main parameters of radar functional blocks at the system calculation and simulation stage. The structure of two-level model in Matlab and Simulink environment is considered and its features are described. Results of the radar simulation and justification of main functional blocks parameters are presented on the example of a W-band single-chip automotive radar.

1 Introduction

Automotive driver assistance systems (ADAS) are widely used in modern vehicles. Estimation of distance, velocity and angular position of different objects on the road underlies the work of any ADAS. For this estimation different kind of systems are used: radars, lidars, hyperspectral imagers, optical cameras and ultrasonic sensors. Each offers advantages and have limitations. Nowadays, Frequency-Modulated Continuous Wave (FMCW) radars play more and more important role on such systems due to their good sensitivity, range resolution, stability, low power consumption and low peak output power. Moreover, radar technology is an environmentally robust solution and can serve as an alternative to optical image sensors when privacy concerns or regulations prohibit using cameras [1]. Modern level of development of microelectronic industry allows to produce highly-integrated single-chip radars in W-range with reasonable cost which can be widely used in ADAS.

First step in FMCW radar design is calculation and system-level simulation of the whole radar structure. At this step, main parameters of all radar functional blocks are determined. Development time and cost depend on the accuracy and completeness of the calculation. The more accurate first step of development, the less development iterations are required to meet the technical requirements for designed radar. Also, system simulation is a very important step in single-chip radar design. Its results form the basis of the requirements for the main radar functional blocks for designers.

To perform system simulation different programs can be used. Main criteria of choose one of them — time and accuracy of simulation. Matlab and Simulink provide a powerful platform for complex radar system simulation and calculation and can be used to perform it with minimum time spend [2].

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2 FMCW radar operation basics

FMCW radar is able to determine distance to the target, its speed and relative angle coordinates simultaneously. Radar of this type radiates narrowband signal with linear frequency modulation (known in the literature as chirp). Figure 1 describes modulation scheme of FMCW radar.

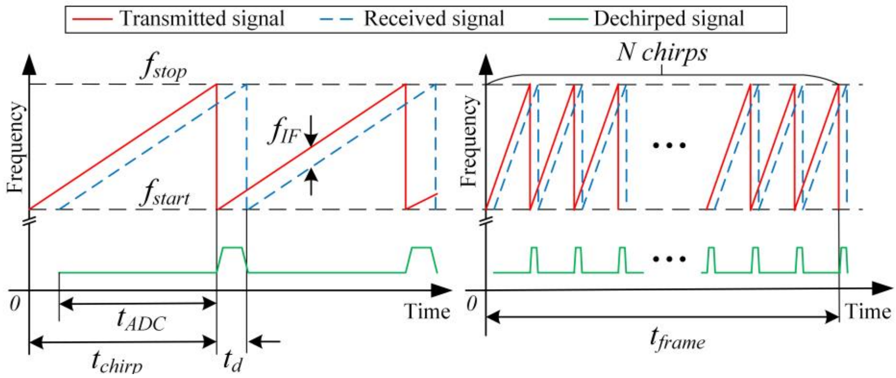

Fig. 1. Sawtooth modulation scheme of FMCW radar: in chirp (a) and frame (b) time scale.

Reflected signal is a copy of radiated signal (see Figure 1, a) delayed by time t_d that is direct proportional to the distance to the target D

$$t_d = 2D/c, \tag{1}$$

where c — speed of light.

Reflected signal is supplied to the receiver input, amplified and fed to one of the mixer inputs. Radiated signal is supplied to the second mixer input without delay. Beat signal is formed at the mixer output with the intermediate frequency (IF)

$$f_{IF} = St_d = \frac{2DB}{ct_{chirp}}, \tag{2}$$

where $B = f_{stop} - f_{start}$ — bandwidth;

$S = \frac{B}{t_{chirp}}$ — chirp slope;

t_{chirp} — modulation time.

Mixer output signal is digitized in the time t_{ADC}, then Fast Fourier Transform (FFT) is performed to determine distance to the target in accordance with (2).

While target moves relative to the radar received signal contains additional component (Doppler frequency). To determine target velocity, it is necessary to analyze received signal over N chirps which make up a frame (see Figure 1, b). Signal samples are recorded in the matrix by the way shown in the Figure 2. Samples in each row of the matrix correspond to the one chirp. Samples in each column — to the same moment of each chirp in the frame.

After filling in the entire matrix a two-dimension FFT is performed to obtain Range-Doppler matrix (see Figure 2). Target detection in obtained matrix is carried out using special algorithms. Most common algorithm with low computation complexity for automotive radar — Cell-Averaging Constant False Alarm Rate (CA-CFAR) [3]. In this work classic CA-CFAR algorithm is used.

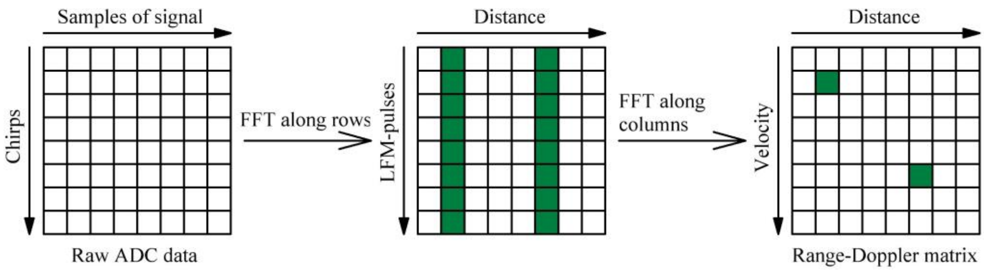

Fig. 2. Range-Doppler matrix creation process.

To determine the angle of arrival of a reflected signal from the target it is necessary to use several receiving channels. An increase in angular resolution requires an increase in the number of receiving channels, which leads to the greater power consumption and crystal area. Multi Input Multi Output (MIMO) radar architecture can be used to reduce this negative effect. Additional "virtual" receiving channels are formed in MIMO radar using greater number of transmitters and special signal processing [4]. It allows to achieve satisfactory angular resolution without a critical increase of receiving channels number. Third FFT among detected targets in the Range-Doppler matrix (see Figure 2) of each "virtual" channel is performed to determine the angle of arrival of the reflected signal.

3 High-level system model

This section describes two-level system model of FMCW radar using Matlab and Simulink.

3.1 First-level model using Matlab

3.1.1 Model description

First-level model in Matlab allows to determine main time and frequency parameters of the radar and perform quick simulation to check obtained values. Also, model allows to check correctness and effectiveness of the digital signal processing algorithm. Block diagram of the first-level model is shown in the Figure 3.

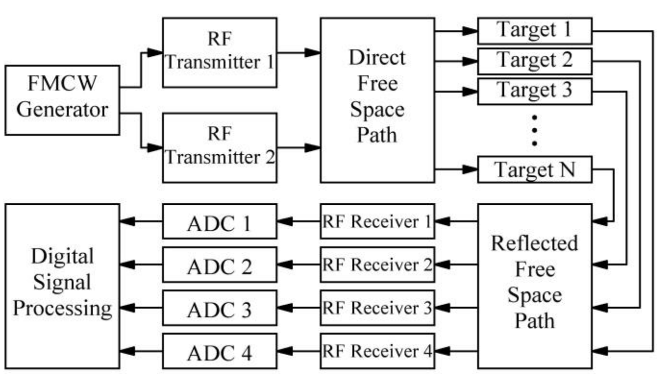

Fig. 3. First-level model block diagram.

The model is built according to the MIMO radar scheme and contains two transmit and four receive channels which forms eight "virtual" receiving channels. The position of the receivers and transmitters is set by the user which provides possibility to create any MIMO radar configuration.

FMCW Generator forms complex signal (radio-frequency pulse with sawtooth frequency modulation) which is fed to RF Transmitter input. From its output, amplified signal goes to Direct Free Space Path that introduces attenuation and phase shift into the signal according to transmitter and target position. Such calculation is performed for each combination of target and transmitter. Then, signal goes to Target models that calculate reflected signal according to Radar Cross Section (RCS) of targets. The number of target and their position can be chosen by designer. Reflected signal from each target goes to Reflected Free Space Path that introduces attenuation and phase shift according to target and receiver position (for all targets and receivers combinations).

Four RF Receivers amplify received signal and form beat signal with IF (2), that goes to the inputs of four Analog-to-Digital Converters (ADC). In the model ADC implemented by reducing the sampling frequency an integer number of times. ADC output signals are recorded to the three-dimension data array. Then, digital signal processing is carried out according to the algorithm, described in the section 2 of the work.

Radar model is based on standard Matlab objects which list in the Table 1. Also, Table 1 contains parameters these blocks allow to set.

Table 1. Matlab objects and main functions used in the model.

Radar functional block (see Figure 3)	Object (*function*) name in Matlab	Parameters
FMCW Generator	phased.FMCWWaveform	Chirp time, bandwidth, model sampling frequency
RF Transmitter	phased.Transmitter	TX output power and gain
	phased.Platform	Transmitter position
Direct Free Space Path	phased.FreeSpace	Radar operating frequency, model sampling frequency
Reflected Free Space Path		
Target	phased.RadarTarget	Target RCS, radar operating frequency
	phased.Platform	Position and velocity of target
RF Receiver	phased.ReceiverPreamp	RX gain and noise figure, noise temperature
	phased.Platform	Receiver position
	dechirp	—
ADC	—	ADC sampling frequency
Digital Signal Processing	phased.CFARDetector2D	Training and guard cells number, probability of false alarm
	fft2, fftshift	FFT window size

MIMO structure with two transmitters and four receivers is implemented in the model. Radar has time division multiplexing [4] and distance *d* between receivers is λ/2. This provides a theoretical angular field of view of 180°. Figure 4 shows antennas configuration used in first-level model.

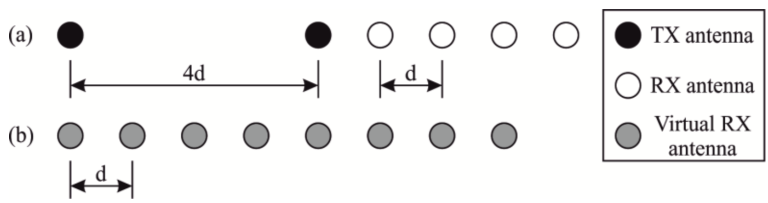

Fig. 4. MIMO radar antenna configuration: real (a) and virtual (b)

As an example, main parameters of automotive parking radar were calculated with the following initial parameters:

— detection range (d_{min}, d_{max}): 0.1 — 10 m;
— range resolution (d_{res}): 0.04 m;

— minimum RCS of target: 0.1 m^2;
— unambiguous velocity range (V_{max}): –4.5 — 4.5 m/s;
— velocity resolution (V_{res}): 0.6 m/s.

Calculation of the main radar parameters is carried out in the model according to following expressions [5]:

$$B = \frac{c}{2d_{res}}; T_{chirp} = \frac{\lambda}{4V_{max}}; S = \frac{B}{T_{chirp}}; T_{frame} = \frac{\lambda}{2V_{res}}; F_{IF\,max} = \frac{S2d_{max}}{c}, \quad (3)$$

where $\lambda = c / f_{start}$ — wavelength;

$F_{IF\max}$ — maximum intermediate frequency.

Following values are obtained according to the initial parameters: B = 4 GHz, T_{chirp} = 100 µs, S = 40 MHz/µs, T_{frame} = 1.6 ms, $F_{IF\max}$ = 2.7 MHz.

3.1.2 Simulation results

Required transmitter power, transmitter and receiver gain, maximum receiver noise figure, number of training and guard cells in 2D CA-CFAR algorithm are determined during simulation. In addition, radar operation correctness is checked. Main results of simulation of the radar with specified parameters (see section 3.1.1) are shown in the Figure 5.

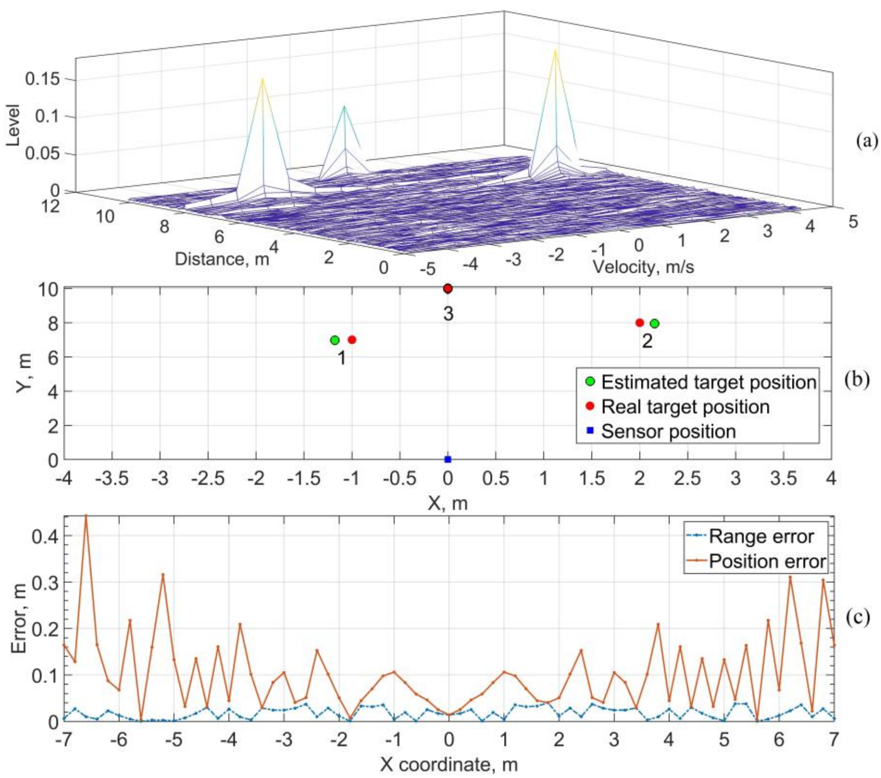

Fig. 5. FMCW first-level model simulation results: range-Doppler plot (a), result of targets location estimation (b) and dependence of target position and range estimation error from X coordinate with fixed Y coordinate (c).

Optimization of radar parameters is performed based on the target position estimation error (see Figure 5, c). Designer is able to change any parameter of the radar model (such as chirp time, bandwidth, receiver noise figure etc.) and control all main characteristics after short-time simulation using useful figures.

Using designed model was found that for the example radar the necessary transmitter power is 10 dBm, transmitting and receiving antennas gain is 10 dB, minimum receiver gain is 30 dB; maximum receiver noise figure is 15 dB, the number of training and guard cells in the 2D CA-CFAR algorithm is 1 and 2, respectively.

3.2 Second-level model using Simulink

3.2.1 Model description

After determining main parameters of the radar and verifying its detection performance using the first-level model in Matlab (see section 3.1), main parameters of the functional blocks of the radar are determined using second-level model in Simulink which is shown in Figure 6. Designed model is based on the previous presented model in [6].

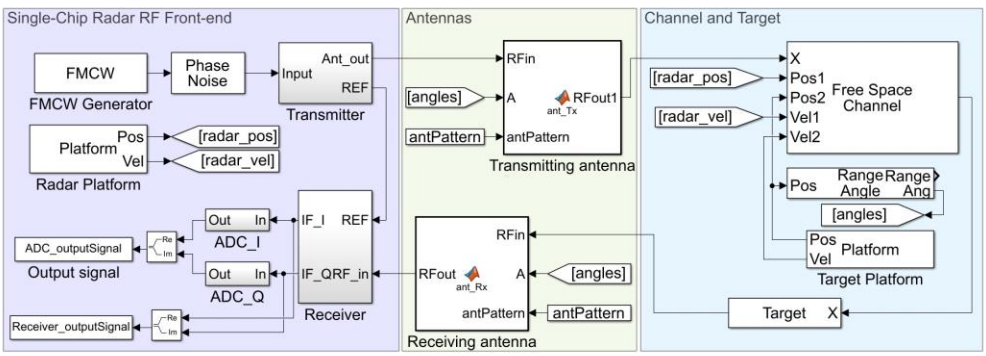

Fig. 6. Second-level model in Simulink.

Second-level model contains three main parts: Single-Chip Radar RF Front-end, transmitting and receiving antennas, model of Channel and Target.

RF Front-end consists of FMCW Generator, transmitter, quadrature receiver and ADCs. Receiver and transmitter models are shown in Figure 7.

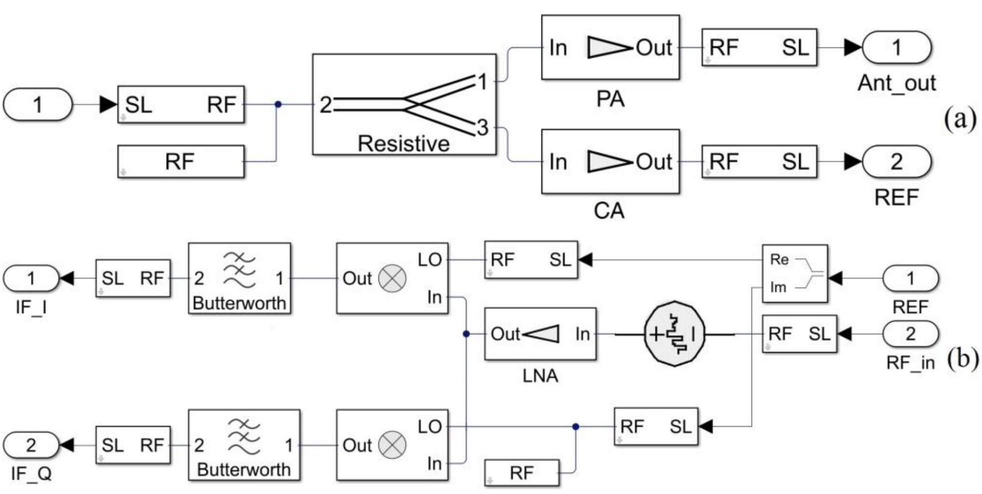

Fig. 7. Transmitter (a) and Receiver (b) models.

Transmitter and receiver models are built using RF Blockset library [7]. These blocks allow to set nonlinear and noise parameters that provides more precise simulation.

Transmitting and receiving antennas models are required to account radiation pattern influence on the radar detection performance. Radiation pattern can be calculated in electromagnetic simulation software (such as FEKO of HFSS) or obtained from antenna measurements. Before starting the simulation radiation pattern is loaded into the model and used during simulation. Relative angular coordinates of target are calculated for operation of both antenna blocks and used to determine gain of antenna in the target direction.

Channel and Target model contains following blocks: Free Space Propagation, Radar Point Target, Motion Platform and Range Angle Calculator. These blocks allow to set target position in Cartesian coordinate system, its velocity and RCS.

The initial data for second-level model are parameters that has been obtained at the previous simulation stage (see section 3.1). These parameters automatically load into Simulink model then simulation is performed. Level and shape of signal are checked in the different points of scheme to determine gain parameters of radar functional blocks. ADC output signals are recorded into variable ADC_outputSignal from Matlab Workspace. After the simulation is completed, digital signal processing is performed using the same algorithm as in the first-level model or simplified algorithm for one chirp.

3.2.2 Simulation results

Figure 8 shows examples of simulation results of second-level model with parameter set described in section 3.1.2: (a) — result of single-chirp processing, (b) — range-Doppler plot and (c) — dependence of Signal-to-Noise Ratio (SNR) of receiver output signal from Low Noise Amplifier (LNA) noise figure at various LNA gain.

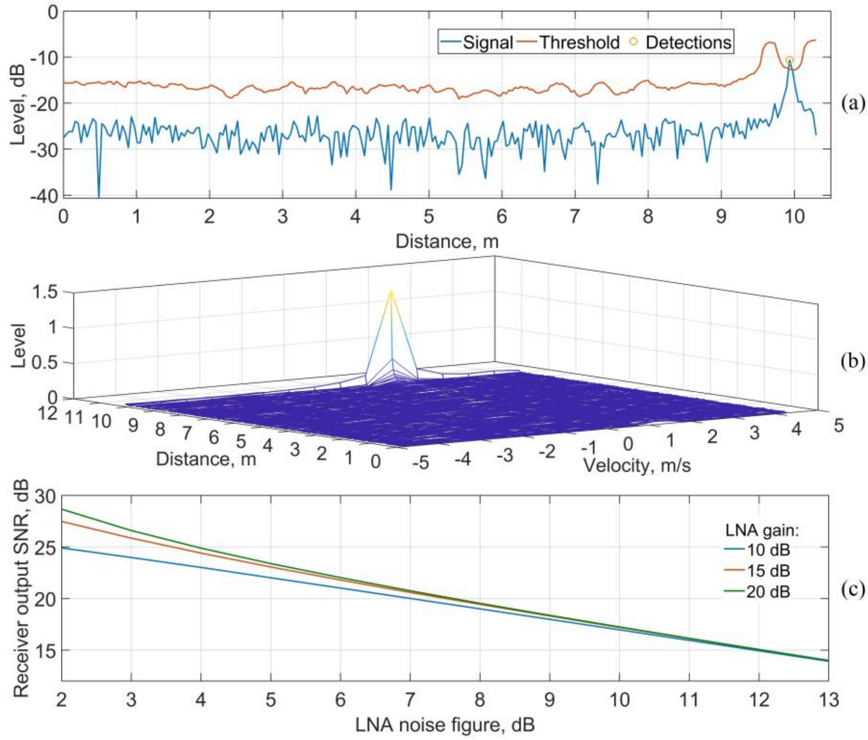

Fig. 8. Examples of second-level model simulation results: range-FFT plot (a), range-Doppler plot (b), and receiver output SNR vs LNA noise figure (c).

Figure 8 (a) shows result of single-dimension CA-CFAR algorithm with probability of false alarm 0.001, number of guard and training cells 8 and 10, respectively. Target at 9.95 m away from the radar with 0.1 m^2 RCS is used during simulation. Gain, noise and nonlinearity parameters of amplifiers, mixers, filters and ADCs are set based on first-level model simulation results.

4 Conclusion

Presented two-level FMCW radar system model allows to determine and justify main parameters of the radar and its functional blocks at the system calculation and simulation stage. The model especially actual while designing single-chip radars, since the number of design iterations and consequently, its final cost and time to market strongly depend on the accuracy of calculation and modeling.

Goal of first-level model using Matlab is to calculate and verificate main time and frequency parameters of the whole radar system and main functional blocks quickly. Simulation time of the first-level model with described in the paper parameters using processor Intel Core i7-4790 @3.6 GHz, 8 GB RAM, Windows 7 and MATLAB R2018a is about 40 seconds for the one iteration (one parameters set).

Goal of second-level model using Simulink is to determine and justify key noise and nonlinear parameters of radar functional blocks (such as low noise amplifier, power amplifier, mixer, ADC) and estimate radar performance considering transmitting and receiving antenna radiation pattern. Simulation time of the second-level model for one chirp is about 18 minutes with model sampling frequency equal to the bandwidth at specified hardware.

Parameters obtained as a result of the simulation in first- and second-level models are used to start development of single-chip radar functional blocks. Also, designed model can be used at later design steps to evaluate the effect of parameters of designed blocks on detection performance before radar production.

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